Studying the Origin of the Kuroshio with an Array of ADCP-CTD Moorings

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LONG-TERM GOALS

Our long-term scientific goals are to understand the dynamics and identify mechanisms of small-scale processes—i.e., internal tides, inertial waves, nonlinear internal waves (NLIWs), and turbulence mixing—in the ocean and their interaction with mesoscale processes such as western boundary currents. We aim to develop improved parameterizations of mixing for ocean models. For this study, our focus is on the origin of the Kuroshio, the interaction among internal tides, internal waves, meso-scale eddies, and the Kuroshio, and the interaction of oceanic processes with the complex topography in Luzon Strait.

OBJECTIVES

The primary objectives of this observational program are to quantify the origin of the Kuroshio and to quantify its properties at the origin and as it evolves downstream.

APPROACH

An array of six subsurface moorings was deployed in June 2012 northeast of the Philippines, where the strong Kuroshio enters Luzon Strait. All moorings were recovered in June 2013. Each mooring had an Acoustic Doppler Current Profiler (ADCP) to measure the velocity field in the upper 450 m. The long-term mooring velocity observations and complementary shipboard survey will help identify the origin of the Kuroshio and its properties before it enters Luzon Strait. We will compare our observations with glider and HPIES observations and with downstream mooring observations east of Taiwan to quantify the evolution of the Kuroshio.

WORK COMPLETED

We recovered six moorings in June 2013 and began data processing and analysis. Results were presented at the ONR workshop in Seattle in August 2013 and at the ONR review in Chicago in September 2013. A manuscript entitled "Modulation of Kuroshio transport by mesoscale eddies at the Luzon Strait entrance" has been submitted to Geophysical Research Letter (Lien et al., 2013).

We conducted the RR-1307 R/V *Revelle* cruise northeast of the Philippines (Luzon Strait) during 30 May – 9 June 2013. We recovered six subsurface moorings and five HPIES, deployed in June 2012.

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We also recovered and deployed a Seaglider, and collected shipboard conductivity-temperature-depth (CTD) and ADCP observations and a bathymetry survey.

RESULTS

Kuroshio Velocity and Transport

Six moorings were deployed along 18°45'N in a zonal section between 122°E and 122°52'E, each roughly 16 km apart, spanning ~80 km at the Kuroshio's entrance to Luzon Strait (Fig. 1). Each mooring was equipped with one upward looking 75-kHz ADCP at 450 m nominal depth. The ADCPs took velocity measurements every1.5 min and recorded averages every15 mins in 8-m vertical bins between 450 m and 45 m depth from June 2012 to June 2013.

Velocity data are low-pass filtered at 10 days to remove tides and high-frequency fluctuations. The monthly averaged meridional current is mostly northward in the observed depth range (Fig. 2). One striking feature is the weak northward current, < 0.5 m s^{-1}, in June 2012, caused by a cyclonic eddy. The maximum northward current (the Kuroshio core) often exceeds 1 m s^{-1}. The Kuroshio core is located at ~122°24'E at the surface, and tilts eastward with increasing depths. The zonal current is about 30–60% of the meridional current.

We compute the Kuroshio transport by integrating the across the moored array of the northward current from the surface to its maximum depth. The annual average northward transport is 15 Sv with a standard deviation of 3 Sv (Fig. 3c). Rapid changes in Kuroshio transport greater than 10 Sv were observed. Between 24 June and 4 July 2012, the transport increases from 7 Sv to 22 Sv in 10 days. Between May and June 2013 transport variations greater than 10 Sv were observed on a *O*(10 days) time scale.

Meso-scale Eddy Effects on Kuroshio Transport

The sea level anomaly (SLA) and the SLA slope at the latitude of our mooring line 18°45'N, reveal clear westward propagation at a speed of ~0.1 m s^{-1} (Fig. 3a and b). The variation of the SLA slope between 122°E and 123°E fluctuates in unison with the observed Kuroshio transport (Fig. 3c). Eight anomalous transport events greater than 3 Sv, one standard deviation, are identified (Fig. 3c). The Kuroshio transport increases when the SLA slope is large, and transport decreases when the SLA slope is small. A linear regression analysis suggests $\delta KT = 6\ x\ 10^{-6}(SLA\ Slope)$, where δKT is the Kuroshio transport anomaly in Sv.

Six eddies within 200 km of the eastern Kuroshio boundary, nominally 18°45'N 123°E, are identified (Figs. 4 and 5). They are tracked as far east as 126°E. Five stall and dissipate at about 124°E. Six anomalous Kuroshio transport events can be explained by the detected eddies (Fig. 5). In particular, the large changes in transport of more than 10 Sv in June–July 2012 (events 1 and 2, see Fig. 3c) and in May–June 2013 (events 7 and 8) are caused by consequent pairs of cyclonic and anticyclonic eddies. These eddies have a typical Rossby number, relative vorticity normalized by the planetary vorticity, of ~0.2. The area integrated eddy kinetic energy is of order TJ $m^{-1}$and the mean current speed is about 0.4 ms^{-1}. The anomalous transport events 5 and 6 in January–April 2013 may be explained by the low SLA to the west of 122°E, and not the westward propagating eddies (Fig. 3a).

Seasonal Cycle of Kuroshio Transport

The linear regression between the SLA slope and the observed Kuroshio transport anomaly is applied to SLA data over the period of 1992–2013 to study the Kuroshio transport anomaly and its seasonal cycle (Fig. 6). The transport anomaly varies between –12 and 7 Sv, with a standard deviation of 3 Sv. Spectral analysis shows a significant peak at a 1-yr period. Monthly averages reveal a seasonal cycle with stronger Kuroshio transport in winter and spring and weaker transport in summer and fall (Fig. 6b).

Eddies within 200 km of the eastern Kuroshio boundary during 1992–2013 are identified. A total of 34 anticyclonic eddies and 60 cyclonic eddies are identified. The relative vorticity computed from the detected eddies is averaged monthly, and shows the strongest anticyclonic in spring and the strongest cyclonic in fall. The time integrated relative vorticity of eddies within 200 km of the eastern Kuroshio boundary is in agreement (Fig. 6d). Our analysis suggests that the Kuroshio seasonal cycle may be partly due to the westward propagating eddies.

IMPACT/APPLICATION

The Kuroshio is well defined north of Luzon Strait as a strong western boundary current. Nonetheless, its origin and the dynamics of its initiation are not well understood. The potential origin of the Kuroshio is complicated by a rich spectrum of oceanic processes, e.g., remotely and locally generated eddies. The Kuroshio carries significant mass, heat, and energy from the tropics to the subtropics and interacts with marginal seas. Therefore it is crucial to understand its origin and dynamics.

RELATED PROJECTS

Generation and Evolution of Internal Waves in Luzon Strait (N00014-09-1-0279) as a part of IWISE DRI: The primary objectives of this observational program are to quantify 1) the generation of NLIWs and internal tides in the vicinity of Luzon Strait, 2) the energy flux of NLIWs and internal tides into the Pacific Ocean and South China Sea (SCS), 3) the effects of the Kuroshio on the generation and propagation of NLIWs and internal tides, 4) the seasonal variation of NLIWs and internal tides, and 5) to study other small-scale processes, e.g., hydraulics and instabilities along internal tidal beams and at the Kuroshio front.

PUBLICATIONS (wholly or in part supported by this grant)

Lien, R.-C., B. Ma, Y.-H. Cheng, C-R. Ho, and B. Qiu. 2013. Modulation of Kuroshio transport by mesoscale eddies at the Luzon Strait entrance, *Geophys. Res. Lett*. [submitted]

Rudnick, D. L., S. Jan, L. Centurioni, C.M. Lee, R.-C. Lien, J. Wang, D.-K. Lee, R.-S. Tseng, Y.Y. Kim, and C.-S. Chern. 2011. Seasonal and mesoscale variability of the Kuroshio near its origin. *Oceanography* **24**(4), 52–63, doi:10.5670/oceanog.2011.94. [published, refereed]

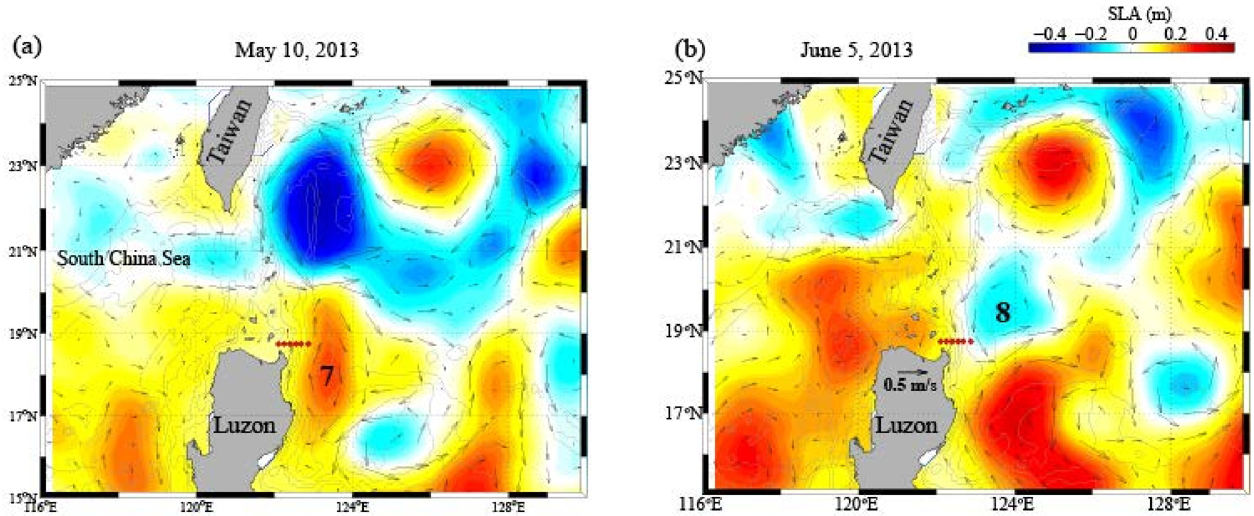

Figure 1: Mooring positions (red dots), AVISO sea level anomaly (SLA) (color shading), and AVISO surface current (vectors) on 10 May 2013 (a) and 5 June 2013 (b). Velocity reference of 0.5 m s^{-1} is labeled. Two eddies that lead to Kuroshio transport anomaly events are labeled 7 and 8.

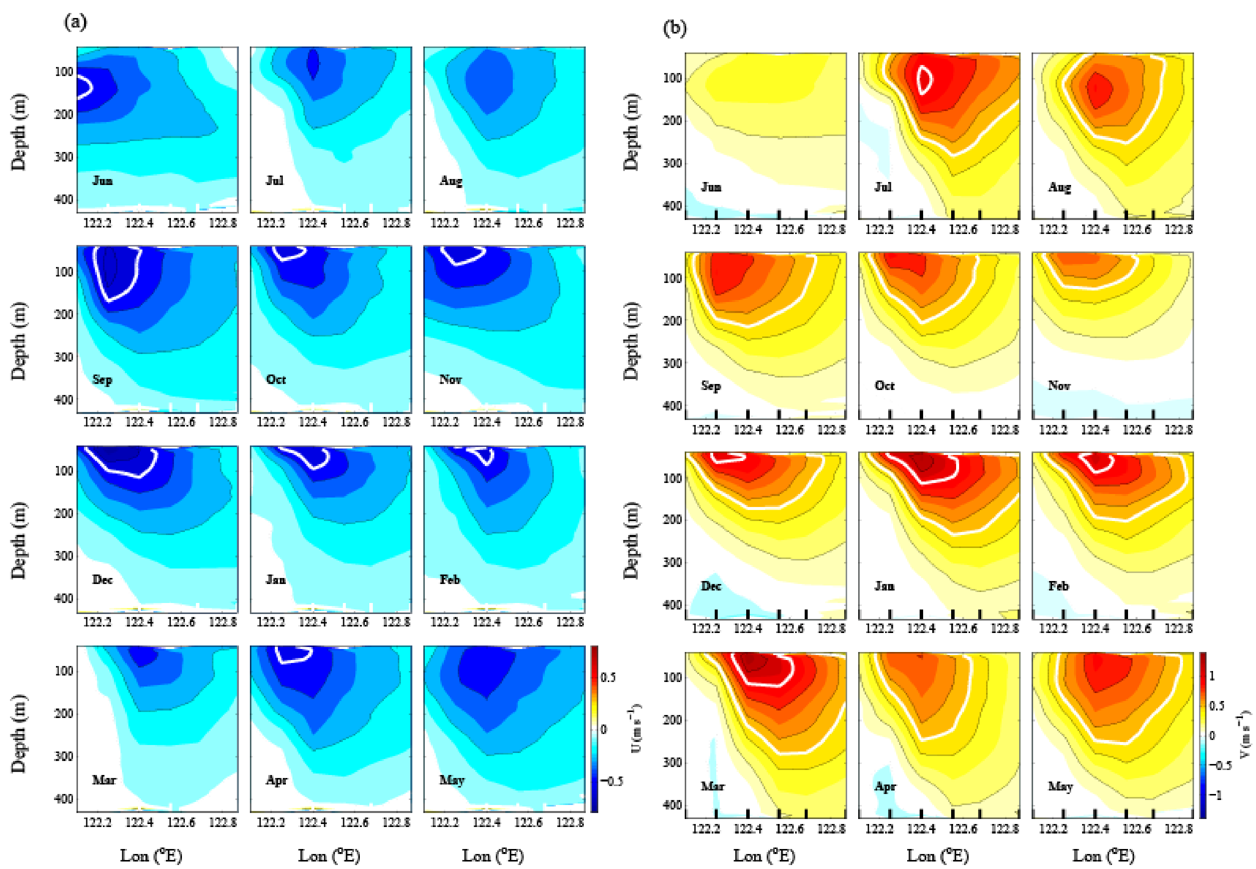

Figure 2: Monthly mean (a) zonal velocity and (b) meridional velocity measured by the moored ADCP array. The black curves are constant velocity contours at a 0.2 m s^{-1} interval. The white curves are 0.5 and 1.0 m s^{-1} velocity contours.

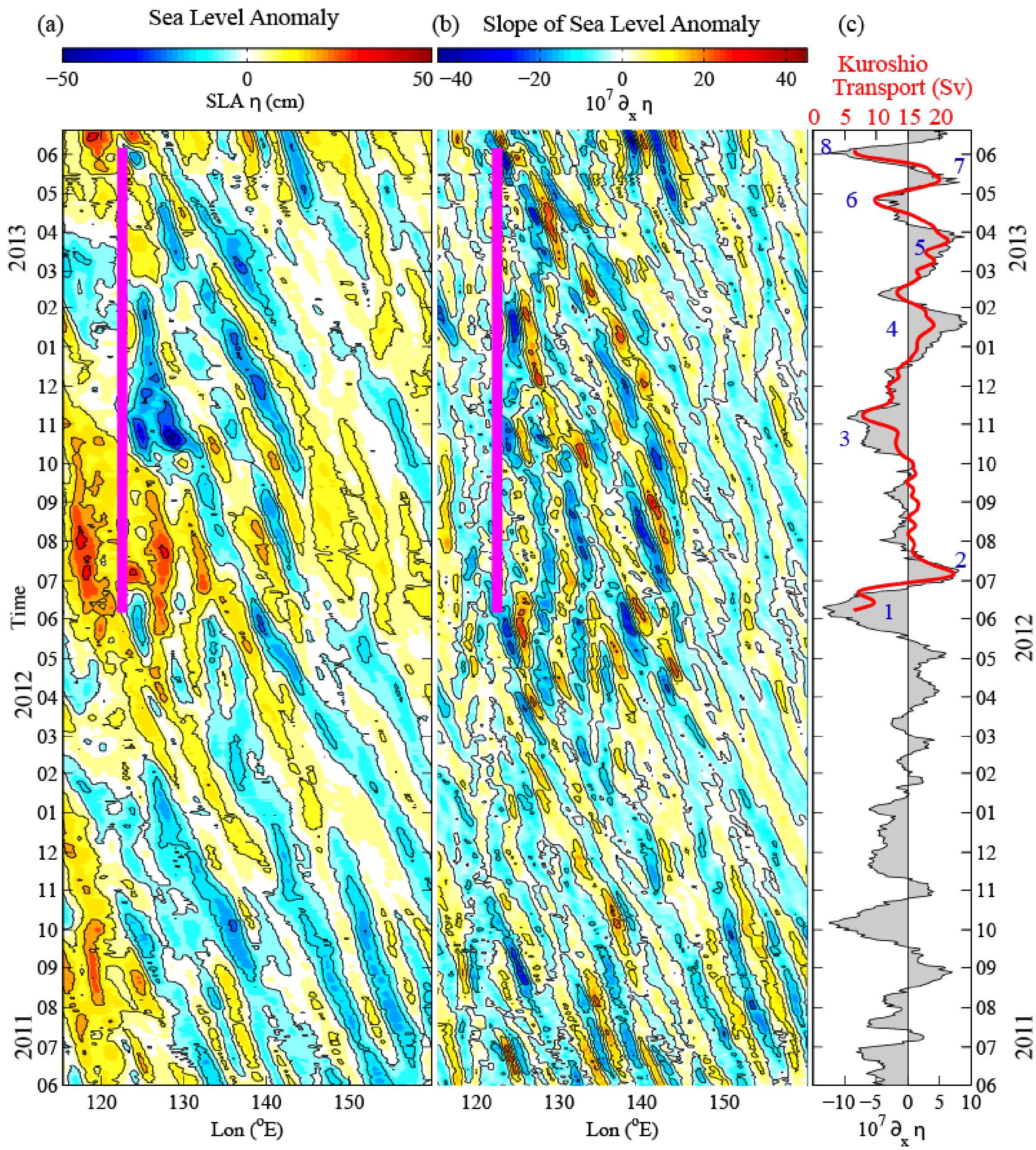

Figure 3: (a) and (b) Sea level anomaly (SLA) and its zonal gradient along 18.75°N, respectively. The magenta vertical line indicates the longitude and observation period of the ADCP moored array. (c) Zonal gradient of the SLA across the moored array between 122°E and 123°E (gray shading), and the Kuroshio transport measured by the moored ADCP array (red curve). Eight events with a transport anomaly exceeding 3 Sv are labeled in panel (c).

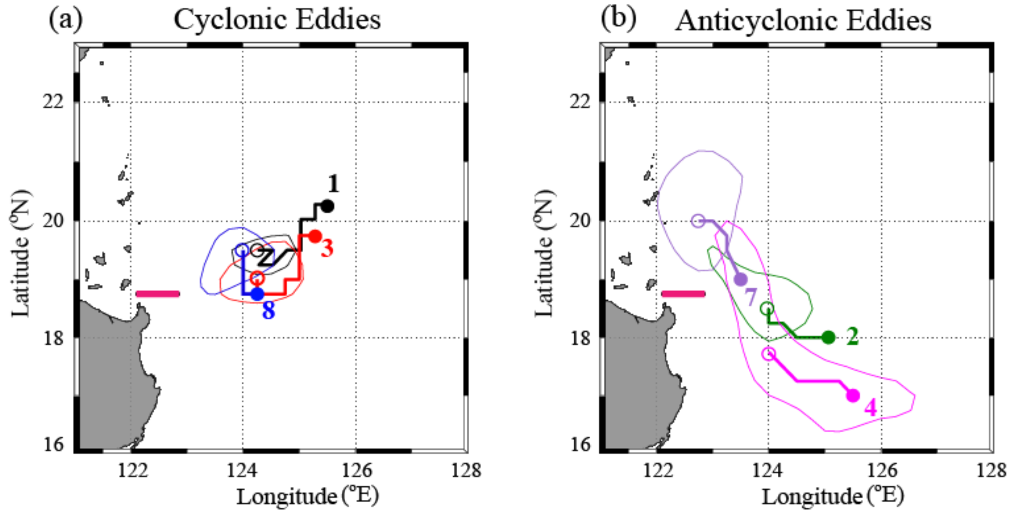

Figure 4: Three cyclonic eddies (a) and three anticyclonic eddies (b) between June 2012 and June 2013. Eddies are labeled corresponding to the anomaly events of Kuroshio transport in Fig. 3c. Magenta line is mooring array position. Color lines show eddy tracks. Dots and circles represent the beginning and the end of eddy tracks. The large closed color loops represent the outer boundary of eddies, defined by the boundary of maximum azimuthal speed.

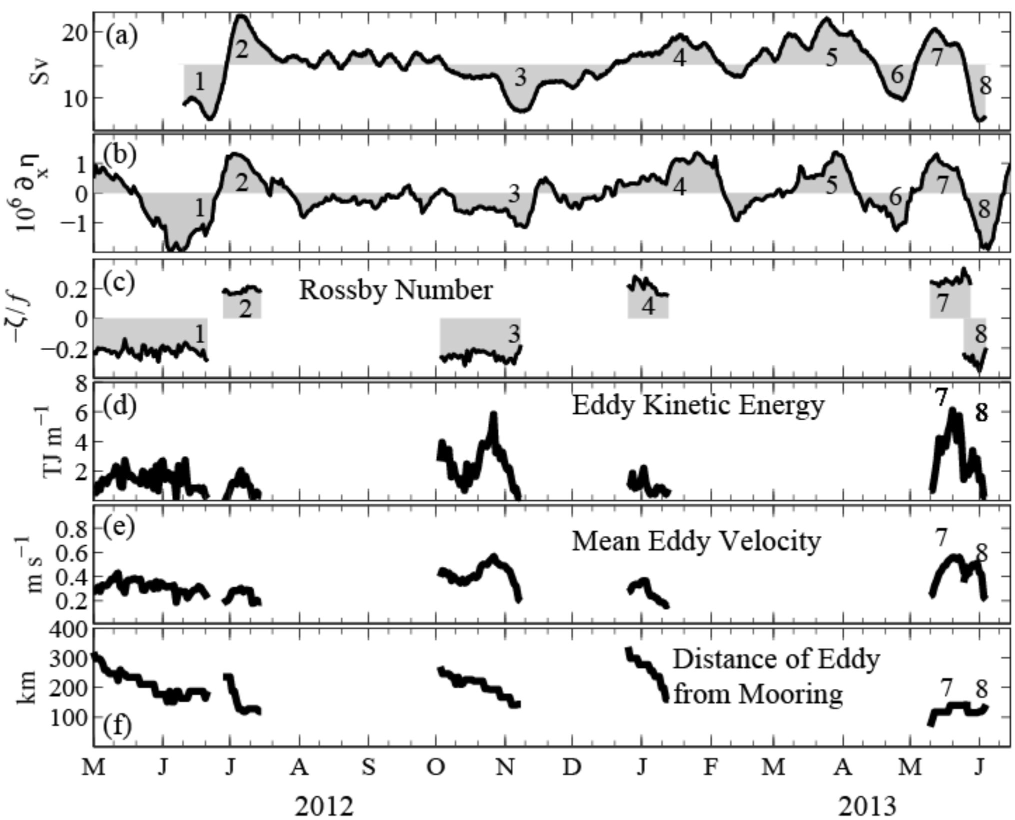

Figure 5. Time series of (a) observed Kuroshio transport, (b) SLA slope between 122°E and 123°E, (c) minus Rossby number, (d) area integrated eddy kinetic energy, (e) area averaged eddy current speed, and (f) distance between the eddy center and the eastern Kuroshio boundary, ~18°45'N 123°E. Kuroshio transport anomaly events and corresponding SLA slope and eddies events are labeled.

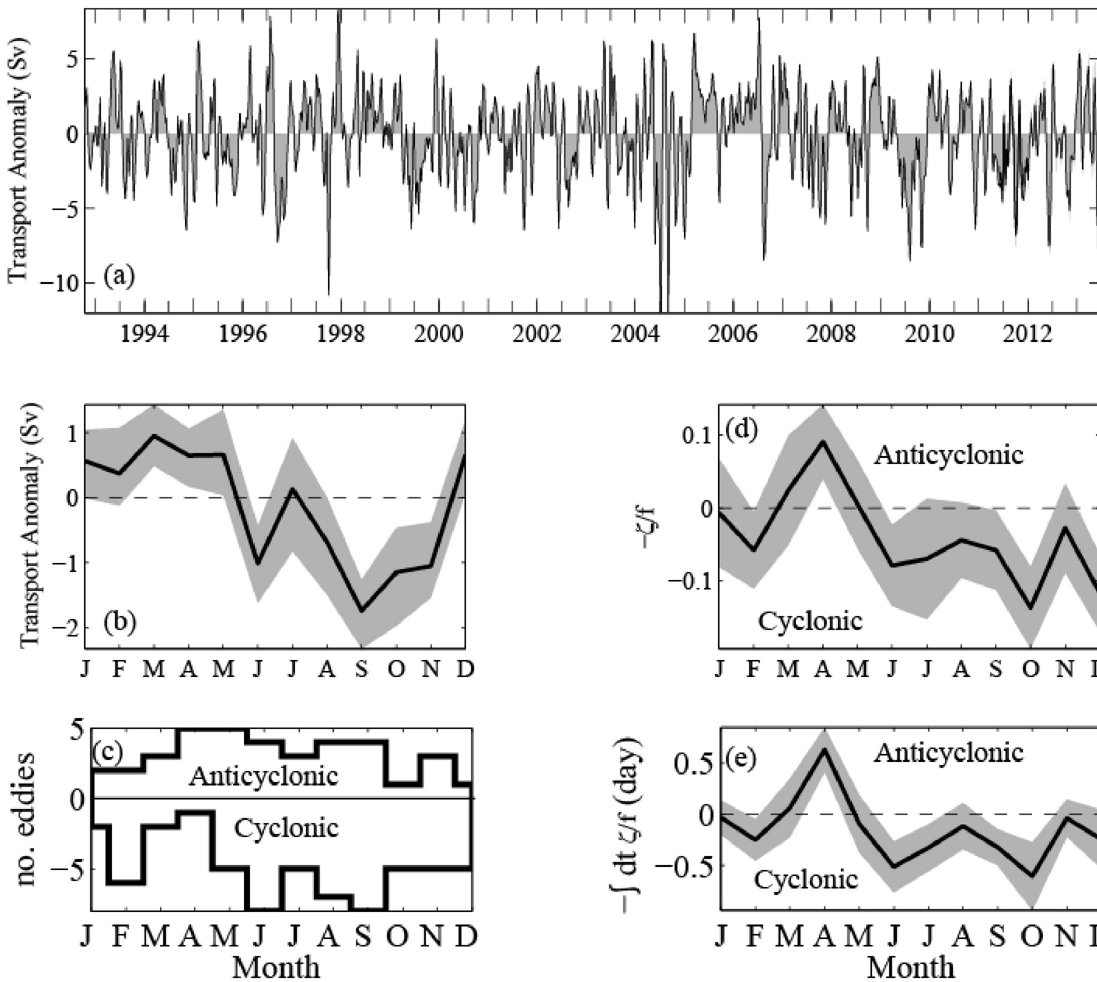

Figure 6: Twenty-one years of AVISO data: (a) Time series of Kuroshio transport anomaly across 18°45'N, computed using SLA slope between 122°E and 123°E, (b) monthly variation of Kuroshio transport anomaly, (c) monthly accumulated number of anticyclonic and cyclonic eddies within 200 km of the eastern Kuroshio boundary, (d) monthly averaged relative vorticity of eddies, and (e) monthly averaged relative vorticity of eddies integrated over the time of eddies within 200 km of the Kuroshio eastern boundary.